

UNDERGROUND STORAGE OF NATURAL GAS IN COAL-MINING AREAS

BY **HENRY P. WHEELER, JR., AND WILLIAM E. ECKARD**

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Henry P. Wheeler, Jr.^{1/} and William E. Eckard^{2/}

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^{1/} Petroleum engineer, Bureau of Mines, Washington, D. C.

^{2/} Petroleum engineer, Bureau of Mines, Franklin, Pa.

INTRODUCTION

Growth of Underground Natural-Gas Storage

Natural gas was first stored underground in Welland County, Ontario Province, Canada, in 1915.^{3/} The following year natural gas in the United States was first stored underground successfully in the Zoar field near Buffalo, N. Y. Only three additional storage fields were in use in the United States in 1930, but by 1940 the number had increased to over 30, and since that time growth has been more rapid. At least 80 fields, with a combined storage capacity of 440,828 MM c.f., were being utilized by 1949.^{4/} In May 1952, 142 storage projects having a capacity of 915,000 MM c.f. were in operation.^{5/} These fields are distributed from New York to California--from Michigan to Texas. In the Appalachian region alone, there are 101 storage fields with a combined capacity exceeding 526,000 MM cu. ft.

Why Natural Gas is Stored

Natural gas is stored in order to be readily available to meet the needs of consumers.

The demand for natural gas is extremely irregular, particularly when a large percentage is distributed to residential customers. The daily average consumption of gas during the winter may be over twice the daily average in the summer; and on an exceedingly cold day, the peak demand is many times the average summer rate. The demand for natural gas for domestic use on a warm afternoon in the summertime is negligible. Peak demands occur on cold winter mornings when houses are being warmed and breakfasts are being cooked.

It is not practical to operate the gas fields that are the primary source of the natural gas, or the pipelines that transport it, at such variable rates. Gas must be produced at rates low enough that the fields will not be damaged by rapid water encroachment, bypassing of less permeable portions of the formation, excessive losses of reservoir energy, and other conditions. Consequently, natural gas is available from its source at a reasonably constant rate. Also, the capacity of pipelines that transport the gas to market is limited by their sizes, working pressures, and other factors. Efficient operation of these lines, which vary in length up to about 1,800 miles and cost many millions of dollars, requires that they be operated insofar as possible at constant rates at or near capacity.

3/ Interstate Oil Compact Commission, A Survey of Underground Natural-Gas Storage Projects in the United States; 1943, 19 pp.

4/ Ball, Max W., Underground Gas Storage; Natural Gas Dept., Am. Gas Assoc., pres. at Spring Meeting, May 1949, 30 pp.

5/ Goodman, John V., Statistics for Storage Operations of Storage Fields; Natural Gas Dept., Am. Gas Assoc., pres. at Spring Meeting, May 1952.

Storage of gas near the point of consumption is one way to equalize the supply and demand. Natural gas can be produced and transported to the point of storage at a constant rate. When the demand is less than that rate, the excess supply is put into storage, from whence it can be withdrawn later to meet demands in excess of pipeline and gas-field capacity. As a result, natural gas can be made available to more customers than could otherwise be served. A typical seasonal cycle of injection and withdrawal is shown in figure 1.6/

Storage of gas also provides a supplemental supply to meet emergencies caused by the mechanical failure of pipelines or other facilities; and better service is assured users of natural gas.

Why Natural Gas Is Stored Underground

Underground storage fields offer two major advantages over other types of natural-gas storage. They are bigger and less costly. They cannot replace other types of storage entirely, because there is a definite need for gas holders, steel-pipe storage, and other types with less capacity; but, if larger capacity is required, underground storage is the answer, provided of course that a suitable field can be found.

A comparison by F. E. Vandaveer and J. J. Schmidt^{7/} of estimated capital costs for various types of storage is shown in table 1. The weighted average cost of storing gas in the 13 underground gas-storage fields referred to in the table is \$0.27 per M c.f. The average capacity of the 13 fields is almost 5,000,000 M c.f., which is also about the average capacity of the 80 fields described by Max Ball in 1949. In recent years, however, the trend has been to larger fields, such as the Oakford storage field near Jeannette, Pa., of the New York State Natural Gas Corp. This field, the largest known to the authors, is reported to have a capacity exceeding 100,000,000 M c.f. It is difficult to visualize storage of a similar volume of gas above ground.

TABLE 1. - Comparison of estimated capital costs
for various types of storage

Type of storage	Cost per M c.f., dollars
Sphere (80 p.s.i.).....	227.00
Steel pipe (2,240 p.s.i.).....	207.00
Gas holder (low pressure).....	156.00
Steel pipe (1,560 p.s.i.).....	48.00
Natural gas in propane.....	32.00
Liquefaction.....	13.00
Salt cavity storage ^{1/}	1.42
Underground storage (water sand).....	.53
Underground storage (depleted wells - 13 fields).....	.02-.50

^{1/} Assuming excavation of 1 M c.f. cavity and disposal of salt brine in deep brine strata. Much less if salt is recovered and sold.

^{6/} Kornfeld, Joseph A., Gas Storage Growth; Oil and Gas Jour., Aug. 2, 1951, vol. 50, No. 13, pp. 41-42.

^{7/} Vandaveer, F. E. and Schmidt, J. J., Underground Storage - and Migration of Natural Gas; Gas, October 1950, pp. 121-128.

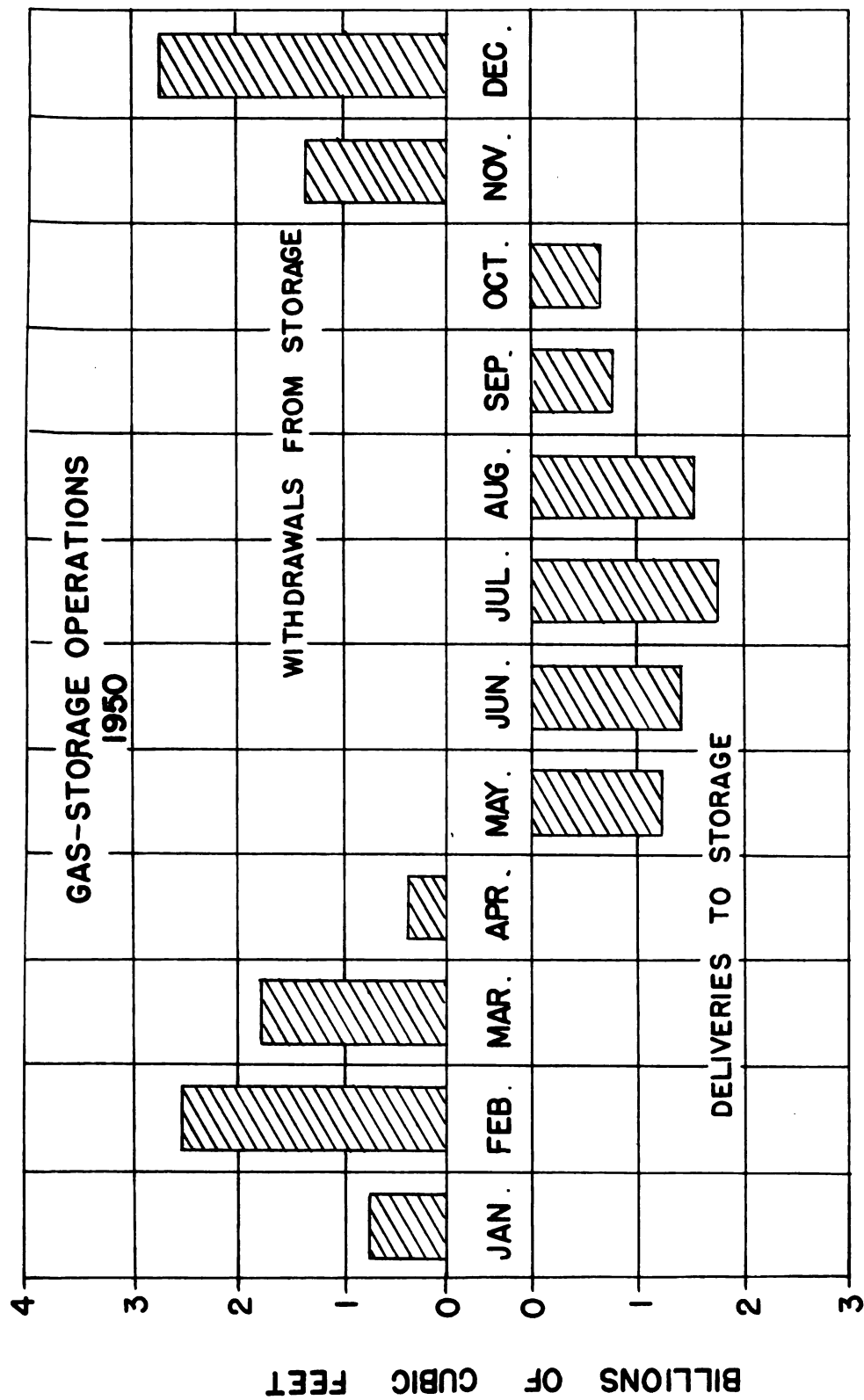


Figure 1. - Typical seasonal cycle of Equitable Gas Co. (After Kornfeld, J. A.)

Why Natural Gas Is Stored Underground in the Appalachian Region

The natural-gas industry in the United States originated in the Appalachian region when, in 1820, a well was drilled near a gas seepage in Fredonia, N. Y., for the express purpose of obtaining a larger flow of natural gas.^{8/} This well was completed at a depth of 27 feet, and the gas was marketed. Natural gas was utilized in West Virginia in 1841, in Ohio as early as 1860, and in several Pennsylvania towns by 1872. Natural gas was first piped to Pittsburgh in 1883 and has contributed substantially to the industrial growth of the region.

As the industrial centers grew and the population increased, more and more people wanted to use natural gas in their homes. The Appalachian region was able to produce enough gas to meet the growing demand for a while, but eventually the local supply became inadequate. In 1951, the region consumed about 14-1/2 percent of all the natural gas consumed in the United States - more than twice as much as it produced - and it has only 2 or 3 percent of the Nation's gas reserves.

Thus, it is necessary to bring gas into the region through long-distance pipelines from Louisiana, Texas, and other southwestern States. Storage capacity is needed to permit efficient utilization of these pipelines, and many suitable exhausted fields are available close to centers of consumption. Through their use, the life of the industry is being prolonged in the Appalachian region, and the inhabitants enjoy an uninterrupted supply of natural gas.

Hazard of Storing Gas Underground in Coal-Mining Areas

Concurrently with the growth of underground gas storage, the coal industry has become increasingly aware of the hazards of coal-mine explosions resulting from the ignition of combustible gas mixtures. No more insidious hazard to coal mining exists than emission into the mine workings of firedamp from the surrounding strata, including the coal itself. Firedamp cannot be smelled, tasted, or seen; usually it is liberated from coal at such low pressure that there is no sound. With rare exceptions, firedamp is methane with only traces of other gases that have no effect on its explosibility. Many hundreds of experiments have shown that the difference in explosibility between firedamp and natural gas is too small to have any significance. The deaths caused by firedamp explosions in coal mines over the hundreds of years of the industry's history are staggering and well nigh unbelievable to persons not associated with the industry.

It is to be expected that coal-mining men should be alarmed by any possible increase in liberation of explosive gas in their mines. That they should want positive proof that gas stored in the ground cannot enter their mine workings is equally to be expected.

^{8/} Ley, Henry A., Natural Gas; Geology of Natural Gas - a Symposium; Am. Assoc. Petrol. Geol., Tulsa, Okla., 1935, pp. 1073-1149.

Purpose of this Information Circular

The coal and natural-gas industries are two of the Nation's greatest. They compete directly in many fuel markets, and the resultant improvements in production, distribution, and utilization are of great benefit to the general public. The coal industry is justly concerned for the safety of its employees. The gas industry is equally concerned regarding the adequacy of the service that it offers to its customers. Underground storage is vital to the natural-gas industry and the many gas consumers in the Appalachian region.

The gas industry does not wish the gas, which it has brought from distant sources and stored, to leak into coal mines or anywhere else. Such leakage would be costly, and the lost gas would not be available to meet the peak demands of the gas consumers.

This report is issued to give information concerning underground gas storage and to point out the authors' conviction that close cooperation between the coal and natural-gas industries is necessary whenever gas is stored near active coal mines. Only through such cooperation can the maximum degree of safety protection be afforded. Operating practices in both industries will undoubtedly change over a period of years. Coal will be mined in new areas; gas will be stored in additional fields. Each industry must give some consideration to the possible effects of its expansion upon the other. By so doing, each can progress and contribute more effectively to the over-all strength of our Nation.

ACKNOWLEDGMENTS

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The assistance and cooperation of the gas companies in the Appalachian Region, through the American Petroleum Institute Eastern District Study Committee on Natural Gas Operating Practices (Underground Storage), J. G. Montgomery, Jr., chairman, and the American Gas Association, Natural Gas Department, Committee on Underground Storage, Fenton H. Finn, chairman, is acknowledged gratefully. John V. Goodman of Equitable Gas Co. was particularly helpful in supplying recent statistics on underground storage.

CHOOSING A FIELD FOR UNDERGROUND NATURAL-GAS STORAGE

Kind of Storage Needed

The size and type of gas storage required depend upon the purpose for which it is intended.

If a storage field is desired to provide gas during an emergency, such as a pipeline break or other equipment failure, the field need not be large, but it must be capable of producing gas for a short period at a high rate of flow. According to Goodman,^{2/} a field with a capacity of 200,000 to 300,000 M c.f. of gas, with a delivery adequate to compensate the greatest probable interruption, would be the ideal storage unit for this purpose.

If storage is required to smooth out the seasonal variations in supply and demand, a larger field may be required, depending upon the magnitude of the variations. This type of storage must be capable of producing gas for a sustained period of several months. Goodman has cited Equitable Gas Co. Unit No. 3 as an example. It has a capacity of 2,800,000 M c.f. and an initial delivery rate of 40,200 M c.f. of gas per day. The larger storage fields are of this type.

Where to Look for a Storage Field

Underground storage fields in the United States have been developed from depleted or partly depleted gas fields, oil fields, and abandoned noncommercial gas fields, and also in formerly untested water sands. The old fields have demonstrated their capability of holding gas under pressure at one time; and, unless they have been irreparably damaged through indiscriminate drilling and completion of wells, they may be developed into storage fields. In many cases, the original wells in the field may be used again in the storage operations. Also, the fields may already be connected to existing pipeline facilities.

The usual practice is to search for a suitable storage field as near the market as possible; however, if a major pipeline serves more than one market, storage may be desirable at a point that will enable the field to serve over one market. Thorough study of all depleted gas fields along the transmission lines and within a reasonable distance of the markets may disclose a field suitable for storage. Max Ball has suggested that a large transmission company might afford to go as far as 300 or 400 miles from its markets to obtain a suitable storage field, but most of the present fields are less than 200 miles from the markets they serve. In some cases, two or more small fields may be used if one large enough cannot be found.

If a suitable depleted gas field cannot be found within the area selected for a storage project, it may be necessary to consider some other form of underground storage. In the Doe Run and Muldraugh storage fields in Kentucky, gas is being stored in sands that contained little or no natural gas originally. This idea of storing gas in a water sand has gained considerable popularity in recent months, and one such project in Kankakee County, Ill., with an anticipated cost of 36 million dollars and an estimated capacity of 90,000,000 M c.f. is under consideration at present.

^{2/} Goodman, John V., Ten Years of Underground Gas Storage: Gas Age, May 3, 1945, pp. 33-37, 80-84.

Gas also may be stored in depleted, partly depleted, or even active oil fields. A good example of this type of storage is the Playa del Rey field in California, which did not contain a gas cap originally; but part of it is being used today for storing natural gas. In the Bammel field, Harris County, Tex., natural gas is being stored in a field that is currently producing liquefied petroleum products through a cycling plant. The stored gas will help to maintain the pressure in the gas-distillate reservoir.

In Michigan, New York, Texas, and perhaps some other States, liquefied petroleum gases (butane and propane) are being stored in artificially created caverns in massive salt formations. The cavities are formed by mining or by dissolving the salt in water circulated through wells drilled from the surface. In at least one field, the brine solution displaced by the liquefied petroleum gases is stored in a sand formation, from whence it can be recovered and used to maintain the pressure in the cavern when the liquefied petroleum gases are withdrawn. This method may be applicable to the storage of natural gas. It is not in use now, however, and its possibilities are not known.

Requirements of a Gas-Storage Field

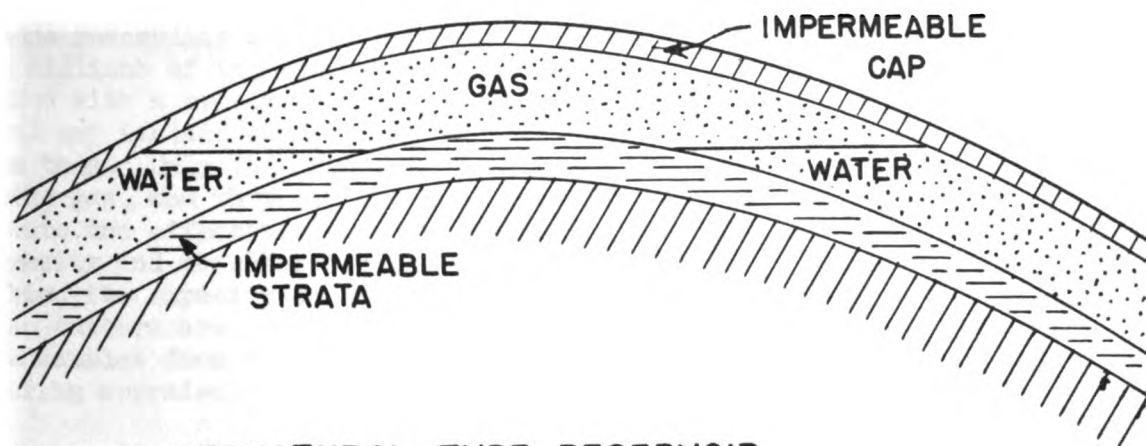
It has been stated previously that a storage field should be near the market it serves and large enough and capable of producing gas rapidly enough to meet the demands caused by equipment failures or seasonal variations in temperature. A field may meet all of the above requirements, however, and still be useless as a storage field--if it is not gas-tight.

It is self-evident that most depleted gas fields were gas-tight before they were drilled; otherwise, gas could not have accumulated in them. Gas, which tends to migrate upward, has been prevented from so doing by an impermeable rock formation. In some fields the impermeable formation overlies a separate permeable formation, and the gas is trapped in anticlines, domes, and other structures created by folds in the rock strata. In other fields the gas is trapped in formations that have variable permeability, and the impermeable portions of the formation prevent migration of the gas from permeable lenses. Both types of fields are being used for storage in the Appalachian region. Idealized cross sections showing the relationship of the permeable and impermeable formations in the two types of fields are shown in figure 2.^{10/}

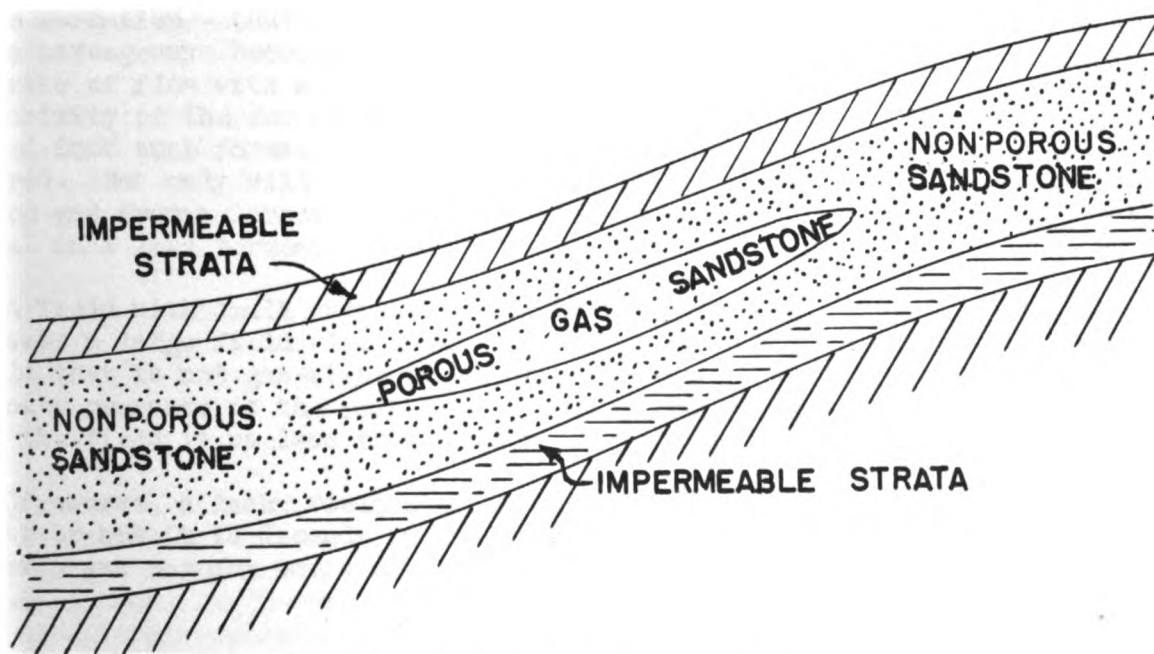
Whether or not a field is gas-tight after it has been depleted depends upon the condition of the wells that exist in the field. In some depleted fields, casing (pipe) has been pulled from the wells and salvaged, leaving the open hole unprotected. Other wells have been plugged with lead or wooden plugs or with cement; some have merely been filled with dirt and debris.

In addition, there may not be any surface indication of the old wells. Cultivated fields, highways, houses, barns, and other structures may be located directly over them. Unless the history of a depleted field is known and the wells can be found and reconditioned if needed, the risks occasioned by improperly abandoned wells may make the field economically unsuitable for consideration. A storage field must be gastight.

^{10/} Murdy, R. J., The Underground Storage of Gas; Mine Inspectors Inst. America Wilkes-Barre, Pa., June 9, 10, and 11, 1952.



STRUCTURAL-TYPE RESERVOIR



POROSITY LENS-TYPE RESERVOIR

**Figure 2. - Types of gas fields used for storage in the Appalachian region.
(After Murdy, R. J.)**

The capacity of a field is determined by its areal extent, the thickness of the formation in which gas can be stored, and the effective porosity of the formation. Contrary to some popular opinion, the formation in which gas occurs may not contain large cavities or caverns. In many fields, gas is found in sandstone resembling that used in constructing buildings; the gas is present in the millions of interstices between the grains of sand. Part of the space is filled with a cementing material which holds the grains together, and this material may isolate some of the interstices so that there is no passageway between them. Only the interstices that are interconnected are effective in producing gas, and they are the only ones in which gas can be stored. They constitute the effective porosity of the formation. Where information regarding the porosity and thickness of the formation and the areal extent of a field is available, its capacity to store gas at various pressures can be calculated. If these factors are not known, they can be determined by laboratory analysis of rock samples from the formation, electrical well-logging devices, and engineering appraisals.

Another important characteristic is the deliverability of the field. In other words, how rapidly can gas be produced from it, or conversely, how rapidly can gas be injected into it without building up an excessive pressure at the wells? This can be determined in part by the number of wells drilled in the field and the pressure at which gas is stored. The rate at which gas will flow through the formation itself, however, depends directly upon the permeability of the formation - that property that is determined by the size and arrangement of the passageways between interstices. If the passageways will accommodate a high rate of flow with a relatively low pressure drop between interstices, the permeability of the formation is said to be high. The deliverability of wells drilled into such formations is correspondingly high, and fewer wells are required. Not only will each well produce gas at a higher rate, but each will produce gas from a larger surrounding area in a highly permeable formation than it will in a less permeable one.

A field with small capacity and high deliverability is suitable for some purposes; a large field with less deliverability is suitable for others - but a field that is not gas-tight is suitable for none. Thus, ability to hold gas under pressure is the principal requisite of a storage field. If it will leak, the field is useless to a company that wishes to store gas.

Of course, a leaky field also may be hazardous to nearby coal mines; whether or not it is depends on how the gas leaks and where the gas goes. Neither a gas company nor a coal-mine owner wants or can afford a leaky storage field.

DEVELOPMENT OF A GAS-STORAGE FIELD

Legal Right to Store Gas Must be Obtained

If a gas company does not already have the legal right to store gas in an underground formation, that right must be obtained. Many leases were obtained from land owners long before the storage of gas underground was contemplated, and storage rights are not provided therein. Usually, however, land owners are willing to extend these rights and thus prolong the receipt of income from a source that otherwise would be depleted.

In Illinois, Oklahoma, Kansas, and New Jersey, the benefit of underground gas storage to the general public has been recognized, and laws have been passed extending the right of eminent domain to underground gas-storage fields. Thus, storage rights can be obtained by condemnation proceedings if necessary to serve the best interests of the public; however, such proceedings rarely are employed.

Finding and Reconditioning Old Wells

The finding and reconditioning of old wells in a depleted field are vital factors in determining whether or not it will be successful in its new role. An undiscovered or improperly completed well might leak gas from the storage field and cause a loss to the gas company as well as a hazard to nearby coal mines. Consequently, these operations receive thorough consideration and study by geologists, petroleum and natural-gas engineers, and other skilled personnel of the gas companies. Reworking old wells is costly, but when the success or failure of a multimillion dollar project is at stake, no practice short of the best that is known can be afforded.

Locating abandoned wells is sometimes difficult, when little or no surface trace of the wells remains. Old maps, well-log files, and other old records may provide valuable clues. Royalty owners, lease employees, retired drillers, and other old inhabitants of an area usually are sources of helpful information. Commercial pipe detectors, wartime mine detectors, dip needles, and magnetic compasses are particularly useful. With this equipment, engineers can find the exact location of many abandoned wells and the approximate location of others. Some wells can be found only by extensive excavation with a bulldozer, and gas companies have dug up several acres of land in some instances to find abandoned wells; the gas company's engineers must be satisfied that all of the wells in a field have been found before they proceed to develop it for gas storage.

After the wells are found, their mechanical condition is determined; if necessary, they are plugged or reconditioned. This is a costly endeavor but is fully justified. A well in an active gas field must be completed to last for the life of the field, whereas a well in a gas-storage field must be completed to last indefinitely.

Completion practices vary in the Appalachian region according to conditions encountered in the wells. Figure 3 illustrates typical casing and cementing methods used by one company.¹¹ Both the surface and production strings of casing are cemented to the surface, providing a double string of cemented pipe through coal measures. This method affords excellent protection against the loss of gas from storage into coal measures, water sands, or elsewhere. Completion methods used by other companies vary somewhat from that shown in figure 3, but all must protect against leakage.

The problems of drilling and completing oil and gas wells through coal beds are not new. The Director of the Bureau of Mines called a meeting of coal operators and oil and gas operators in 1913 to discuss precautionary methods to be taken when drilling oil or gas wells through workable coal

¹¹/ Work cited in footnote 10.

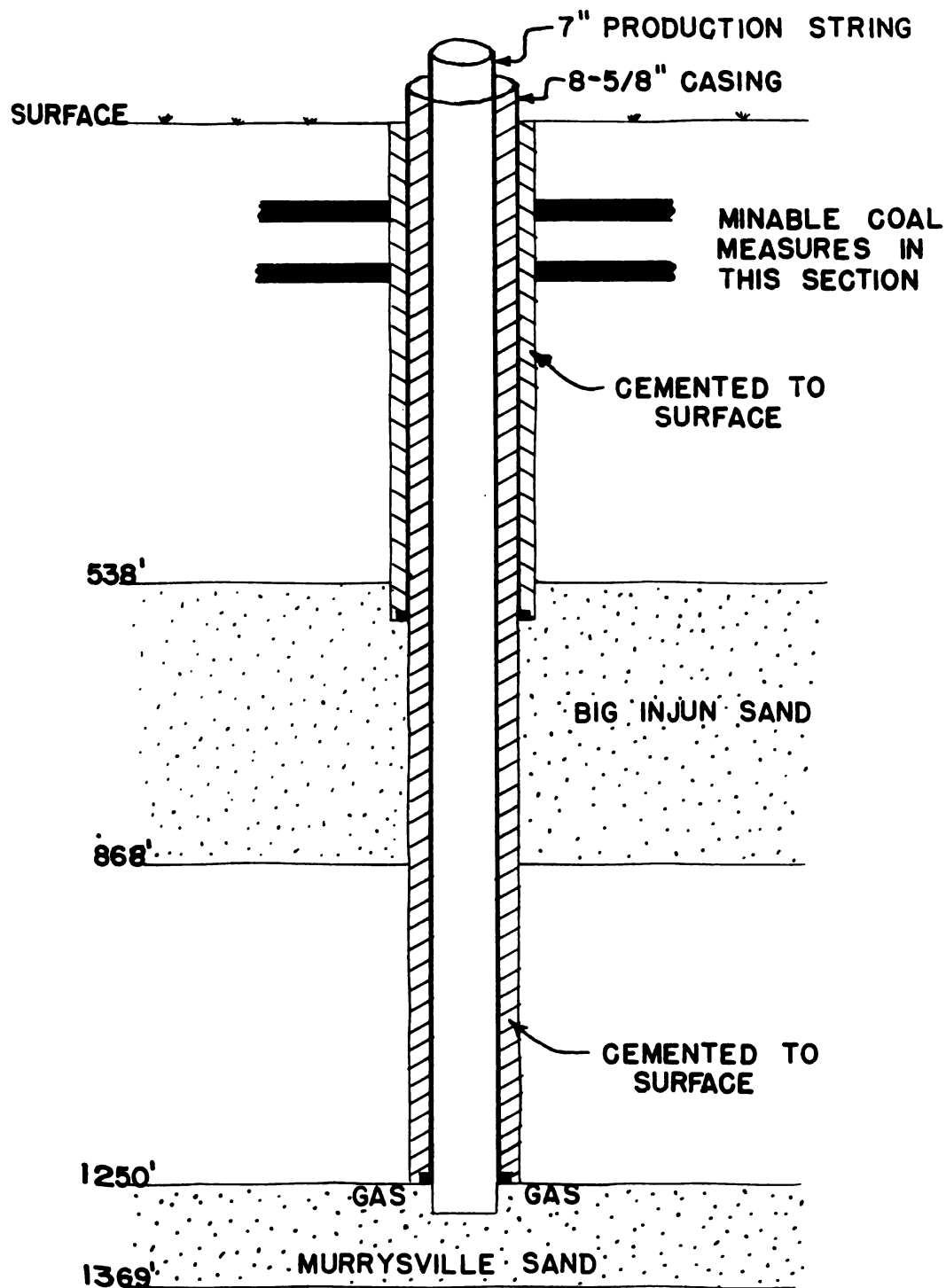


Figure 3. - A method of cementing casing in a gas well.
(After Murdy, R. J.)

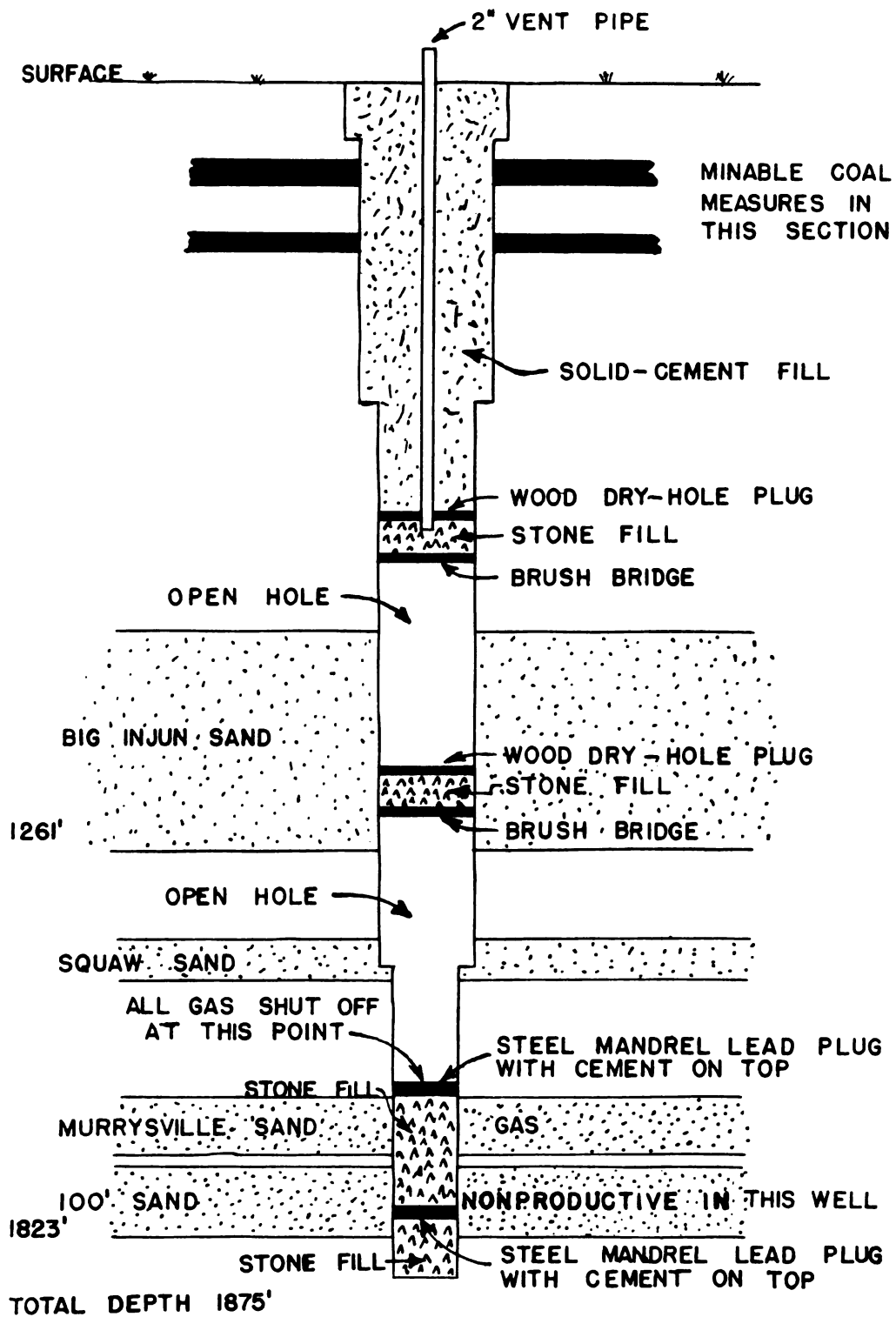


Figure 4. - A method of plugging a gas well for abandonment.
(After Murdy, R. J.)

beds.^{12/13/} Later, in April 1928, the American Institute of Mining and Metallurgical Engineers made a report on the subject. In November 1929, the Bureau of Mines issued an Information Circular^{14/} describing, in part, regulations governing the drilling of oil or gas wells through workable coal beds in several States, notably West Virginia. It can be seen, therefore, that the subject has been exposed to much discussion by competent authorities, and regulation by several States. Present-day drilling and completion practices are the results of many years of experience.

Plugging wells that are unsuitable for one reason or another for use in a storage field is a kind of reconditioning. As a matter of fact, some wells that are ultimately plugged require considerable reconditioning - redrilling and cleaning out - before they can be plugged. Figure 4 illustrates a method by which one gas well was plugged for abandonment;^{15/} however, this is not the only way that a well can be plugged effectively, and it must not be considered a standard for the region.

New Construction

Although finding a suitable field and reconditioning old wells are primary requisites of an underground gas-storage project, they are not the only factors to be considered. Pipelines must be built, in many instances, to serve as connecting links between the storage field and the distribution system. Compressor stations to boost the gas pressure are frequently needed. Gas-dehydration plants may be required to remove water vapor from the gas and thus prevent formation of hydrates in the pipelines. Also, additional wells usually are needed to provide adequate deliverability of gas during peak loads. All of these factors add to the cost of the project. The gas industry cannot afford these expenditures without reasonable assurance that the storage will be gas-tight.

The drilling of new wells in the vicinity of coal mines is of vital concern to coal operators. In drilling these wells, the gas companies are not restricted, as they might be in reconditioning old wells, as to the size of the hole drilled and the resultant casing programs. New wells in gas-storage fields embody all of the best practices and materials known to the industry.

Storage Pressures

In general, gas is stored underground in the Appalachian region at pressures that do not exceed the original pressure of the field in which it is stored. This practice is based on the theory that the field was filled by nature to that pressure and thus has been proved to be gas-tight at that pressure.

^{12/} Hood, O. P. and Heggem, A. G., Proposed Regulations for the Drilling of Gas and Oil Wells; Bureau of Mines Tech. Paper 53, 1913, 28 pp.

^{13/} Rice, G. S., Hood, O. P., and Others, Oil and Gas Wells Through Workable Coal Beds; Papers and Discussions; Bureau of Mines Bull. 65, 1913, 101 pp., 1 pl., 11 figs.

^{14/} Herbert, C. A., Notes on Precautions to Be Taken When Drilling Oil or Gas Wells Through Workable Coal Beds or Through Mine Workings; Bureau of Mines Inf. Circ. 6195, 1929, 8 pp.

^{15/} Work cited in footnote 10.

However, some gas companies are storing gas at pressures that exceed the discovery pressure, and this practice has caused alarm among coal operators who fear that the extra pressure might open new passageways in the underground formation through which gas might escape from storage into their coal mines, with disastrous results.

These fears are understandable. Some underground storage fields resemble domes, with a water seal at the edge. It is possible that enough gas could be forced into such a dome to depress the water, break the seal, and allow gas to migrate into previously barren formations. Also, it is conceivable that enough pressure might be exerted in shallow fields to actually lift the overlying strata and create new passageways within the formation.

No group is better aware of these possibilities than the gas companies themselves. As pointed out previously, they can ill afford to lose gas from storage. These companies maintain staffs of trained engineers and geologists to delineate the fields. Edge wells are drilled to detect the presence of gas. Movement of the water level in each field is carefully watched. Also, engineers can calculate the pressures required to lift the overburden at various depths.

GAS ACCOUNTING IN STORAGE FIELDS

The proof of the pudding is in the eating; and the proof of a gas-storage field is its ability to store gas in times of low demand and make it available to meet the peaks. In many respects, a storage field is similar to a bank, and the gas companies expect to get out as much gas as they put in. Moreover, a company must know how much gas it has in storage at any particular time. Thus, it is necessary to account for the gas as it is injected and withdrawn.

Accurate gas-measurement records of the field's operation are kept. They enable the operator to calculate the volume of gas injected or withdrawn per pound of change in pressure and thus define a standard of performance that can be compared with the performance of the field at any date. This index of performance is known as the "volume-per-pound" relationship. Because of the pressure gradients set up within the formation when gas is injected or withdrawn, the relationship seldom is a straight line, and the withdrawal curve usually lags behind the injection curve.

In spite of the best efforts of the gas companies to account for the stored gas, it must be recognized that orifice meters and other measuring devices are not accurate enough to provide an absolute check against the loss of gas in small quantities, but large enough to create an explosive hazard in a coal mine. It behooves the coal operators, therefore, to be ever on the alert for gas occurrences from whatever source.

CONCLUSIONS

The storage of natural gas underground in coal-mining areas is necessary if the inhabitants of those areas are to enjoy continued use of natural gas in their homes. However, storage fields must be developed with due consideration of the rights and safety of the coal industry.

The authors believe that the only satisfactory solution is complete co-operation between the two industries and their mutual enlightenment through free exchange of information. No doubt, questions will be asked to which no completely satisfactory answer can be given because knowledge is incomplete. When this happens, a joint and vigorous effort should be made to fill in the gaps in information.

The competitive relationship between the two industries must not become a stumbling block in the way of safety and public interest; the natural growth of both should be encouraged.